Absorption of ϕ mesons in near-threshold proton–nucleus reactions

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Abstract

In the framework of the nuclear spectral function approach for incoherent primary proton–nucleon and secondary pion–nucleon production processes we study the inclusive ϕ meson production in the interaction of 2.83 GeV protons with nuclei. In particular, the A-dependences of the absolute and relative ϕ meson yields are investigated within the different scenarios for its in-medium width as well as for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$. Our model calculations take into account the acceptance window of the ANKE facility used in a recent experiment performed at COSY. They show that the pion–nucleon production channel contributes distinctly to the ϕ creation in heavy nuclei in the chosen kinematics and, hence, has to be taken into consideration on close examination of the dependences of the phi meson yields on the target mass number with the aim to get information on its width in the medium. They also demonstrate that the experimentally unknown ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ has a weak effect on the A-dependence of the relative ϕ meson production cross section at incident energy of present interest, whereas it is found to be appreciably sensitive to the phi in-medium width, which means that this relative observable can indeed be useful to help determine the above width from the direct comparison the results of our calculations with the future data from the respective ANKE-at-COSY experiment.

1 Introduction

Studies of modification of the ϕ meson spectral function at finite baryon density through its production and decay in pion–nucleus [1], proton–nucleus [2–6] and photon–nucleus [7–10] reactions have received considerable interest in recent years. Because, on the one hand, the ϕ meson (in contrast to the ρ and ω mesons) does not overlap with other light resonances in the mass spectrum and, on the other hand, the reactions on ordinary nuclei with elementary probes are less complicated compared to heavy–ion collisions especially in the near-threshold energy regime where a small number of possible channels for meson production contributes, one may hope to get from these studies a more clear precursor signals for partial restoration of chiral symmetry–the fundamental symmetry of QCD in the limit of massless quarks [11–13]–and thus to test this prominent feature of QCD as well as to extract valuable information on the nucleon strangeness content [4, 7] and on the kaon in-medium properties [1–4]. Furthermore, the sensitivity of such reactions to in-medium changes of hadron properties, as was argued in [14], is expected to be comparable to that of nucleus–nucleus collisions. The modification of the ϕ properties (mass and width) in matter has been studied in variuos approaches based both on the QCD sum rules [11, 15, 16] and on the hadronic models [17–19]. All these works point at a small mass shift of the ϕ meson in nuclear matter (about 1–2% of its free mass at normal nuclear matter density ρ_0) and an appreciable increase (by a factor of about five–six [17, 18] to ten [19] at density ρ_0) in its in-medium total width compared to the vacuum value ($\Gamma_\phi = 4.45$ MeV). Because of this in the following we will concentrate on the possible determination of the ϕ width in the medium at finite baryon densities. The broadening of the ϕ spectral shape in the nuclear matter could be directly tested by looking at the invariant mass spectra of its decay products. However, because of the strong final-state interactions of kaons from phi hadronic decay $\phi \to K^+K^-$ inside a medium, the authors of refs. [4] and [7] using, respectively, an appropriate nuclear spectral function approach and the BUU transport model have found no measurable broadening of the resulting invariant mass distributions of the emitted charged kaon pairs due to the ϕ in-medium width both from proton–nucleus and from photon–nucleus reactions. Since the dileptons, i.e. e^+e^-, $\mu^+\mu^-$ pairs from phi leptonic $\phi \to e^+e^-$, $\phi \to \mu^+\mu^-$ decay channels, experience no strong final-state interactions with nuclear matter, only the dilepton mass spectra turned out to be sensitive to the ϕ renormalization at the density of ordinary nuclei when the respective low-momentum cuts to the ϕ three-momentum were applied [1, 4, 5]. But the measurements of these spectra are difficult due to the small cross sections for dilepton production events [1, 4, 20]. Another indirect possibility to learn about the in-medium broadening of the ϕ meson has been considered in refs. [2, 3, 6, 8–10]. As a measure for this broadening the A-dependence of the ϕ production cross section in nuclei in proton- and photon-induced reactions has been employed in these works. The A-dependence is governed by the absorption of the ϕ meson flux in nuclear matter, which in turn is determined, in particular, by the phi in-medium width. The advantage of this method is that one can exploit the main decay channel $\phi \to K^+K^-$, having large branching ratio (≈ 50 %), for identification of the ϕ meson in the phi production experiments on cold nuclear matter, like for example, in a completed nuclear ϕ photoproduction experiment at SPring 8/Osaka

[10] or in proton–nucleus experiment [1] at the COSY [21], which is presently being analyzed [22]. It should be noted that the above method has been also recently adopted to study the properties of the ω mesons [23–25] and $\Lambda(1520)$ hyperons [26] in finite nuclei in γ- and p-induced reactions.

Following this method and using present models for the ϕ self-energy in a nuclear medium as well as an eikonal approximation to account for the absorption of the outgoing ϕ meson, the authors of [3] have calculated the A-dependence of the ratio between the total phi production cross section in heavy nucleus and a light one (^{12}C) in pA collisions. The calculations were performed within the local Fermi sea model at energies accessible at COSY and, in particular, at beam energy of 2.83 GeV, which was employed in the recent measurements of proton-induced ϕ production in nuclei at the ANKE-COSY facility [21, 22]. They have been done also with having the poor knowledge about the free cross sections of the relevant elementary reactions $pp \to pp\phi$, $pn \to pn\phi$ at above energies and with neglecting in part the ϕ creation in the two-step processes with an intermediate pions. However, the direct comparison the results of these calculations with the future data from the ANKE-at-COSY experiment [21, 22] to constrain the in-medium broadening of the ϕ meson is troublesome, since they were carried out for the whole available phase space of the phi and did not take into account the actual acceptance window of the ANKE spectrometer that can detect ϕ mesons via decays $\phi \to K^+K^-$ only under forward polar angles in the lab system ($0^\circ \le \theta_\phi \le 8^\circ$) and in a limited momentum range (0.6 GeV/c $\le p_\phi \le$ 1.8 GeV/c) [22]. On the other hand, the new experimental [27, 28] and theoretical [29] results on the ϕ production cross sections in free pp and pn interactions at initial energies of interest have been recently obtained. In addition, the authors of ref. [2] have pointed at the secondary ϕ production channel $\pi N \to \phi N$ as important one in the phi creation in heavy nuclei in near-threshold pA reactions. It is clear that, in order to put a strong constraints on the in-medium ϕ width from comparison the results of model calculations with the future data from the ANKE experiment [21, 22], all of the preceding has to be properly accounted for in such calculations–the main purpose of the present investigation.

In this paper we perform a detailed analysis of the ϕ production in pA interactions at 2.83 GeV beam energy. We present the detailed predictions for the A-dependences of the absolute and relative cross sections for the ϕ creation from these interactions obtained in the framework of a nuclear spectral function approach [4, 30–34] for an incoherent primary proton–nucleon and secondary pion–nucleon phi meson production processes in a different scenarios for the total ϕ in-medium width as well as with imposing the ANKE spectrometer kinematical cuts on the laboratory ϕ momenta and production angles. In view of the future data from this spectrometer, the predictions can be used as an important tool for extracting the valuable information on the phi in-medium properties.

[1] It should be mentioned that the high-energy proton–nucleus experiments, in which the A-dependence of inclusive ϕ meson production on nuclei was studied, are reviewed in ref. [6].

2 The model and inputs

2.1 Direct ϕ production mechanism

An incident proton can produce a ϕ directly in the first inelastic pN collision due to the nucleon's Fermi motion. Since we are interested in the near-threshold energy region, we have taken into account the following elementary processes which have the lowest free production threshold (≈ 2.59 GeV):

$$p + p \to p + p + \phi, \tag{1}$$

$$p + n \to p + n + \phi, \tag{2}$$

$$p + n \to d + \phi. \tag{3}$$

Because the phi–nucleon elastic cross section is rather small [1, 35], we will neglect the elastic ϕN final-state interactions in the present study. Moreover, since the ϕ meson pole mass in the medium is approximately not affected by medium effects [18, 19] as well as for reason of reducing the possible uncertainty of our calculations due to the use in them the model nucleon self-energies [36, 37], we will also ignore the medium modification of the outgoing hadron masses in the present work. Then, taking into consideration the ϕ meson final-state absorption as well as assuming that the ϕ meson–as a narrow resonance–is produced and propagated with its pole mass M_ϕ at small laboratory angles of our main interest and using the results given in refs. [4, 30–33, 38], we can represent the inclusive cross section for the production on nuclei phi mesons with the momentum $\mathbf{p}_\phi$ from the primary proton-induced reaction channels (1)–(3) as follows [2] :

$$\frac{d\sigma^{(\rm prim)}_{pA\to\phi X}(\mathbf{p}_0)}{d\mathbf{p}_\phi} = I_V[A]\left[\frac{Z}{A}\left\langle\frac{d\sigma_{pp\to pp\phi}(\mathbf{p}_0^{'}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi}\right\rangle + \frac{N}{A}\left\langle\frac{d\sigma_{pn\to pn\phi}(\mathbf{p}_0^{'}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi}\right\rangle\right] + \tag{4}$$
$$+I_V[A]\frac{N}{A}\left\langle\frac{d\sigma_{pn\to d\phi}(\mathbf{p}_0^{'}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi}\right\rangle,$$

where

$$I_V[A] = 2\pi A\int\limits_0^R r_\perp dr_\perp \int\limits_{-\sqrt{R^2-r_\perp^2}}^{\sqrt{R^2-r_\perp^2}} dz\rho(\sqrt{r_\perp^2+z^2}) \times \tag{5}$$
$$\times \exp\left[-\sigma_{pN}^{\rm in}A\int\limits_{-\sqrt{R^2-r_\perp^2}}^{z}\rho(\sqrt{r_\perp^2+x^2})dx - \int\limits_{z}^{\sqrt{R^2-r_\perp^2}}\frac{dx}{\lambda_\phi(\sqrt{r_\perp^2+x^2}, M_\phi)}\right],$$

[2] It is worth noting that for kinematical conditions of the experiment [21, 22] the contribution to the ϕ production on nuclei from the phi mesons produced in main primary $pN \to pN\phi$ channels (1), (2) and decaying into the K^+K^- pairs inside the target nucleus is found on the basis of the model developed in [4] to be negligible compared to the overal ϕ yield from primary and secondary phi creation processes calculated for these conditions within the present approach. The latter yield corresponds to the ϕ decays outside the target nucleus.

$$\lambda_\phi(\mathbf{r}, M_\phi) = \frac{p_\phi}{M_\phi \Gamma_{\rm tot}(\mathbf{r}, M_\phi)} \tag{6}$$

and

$$\left\langle \frac{d\sigma_{pN\to pN\phi}(\mathbf{p}_0^{'}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi} \right\rangle = \int\int P(\mathbf{p}_t, E) d\mathbf{p}_t dE \left[\frac{d\sigma_{pN\to pN\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi} \right], \tag{7}$$

$$\left\langle \frac{d\sigma_{pn\to d\phi}(\mathbf{p}_0^{'}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi} \right\rangle = \int\int P(\mathbf{p}_t, E) d\mathbf{p}_t dE \left[\frac{d\sigma_{pn\to d\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi} \right]; \tag{8}$$

$$s = (E_0^{'} + E_t)^2 - (\mathbf{p}_0^{'} + \mathbf{p}_t)^2, \tag{9}$$

$$E_0^{'} = E_0 - \frac{\Delta\mathbf{p}^2}{2M_A}, \tag{10}$$

$$\mathbf{p}_0^{'} = \mathbf{p}_0 - \Delta\mathbf{p}, \tag{11}$$

$$\Delta\mathbf{p} = \frac{E_0 V_0}{p_0}\frac{\mathbf{p}_0}{|\mathbf{p}_0|}, \tag{12}$$

$$E_t = M_A - \sqrt{(-\mathbf{p}_t)^2 + (M_A - m_N + E)^2}. \tag{13}$$

Here, $d\sigma_{pN\to pN\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)/d\mathbf{p}_\phi$ and $d\sigma_{pn\to d\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)/d\mathbf{p}_\phi$ are the off-shell [3] differential cross sections for ϕ production in reactions (1), (2) and (3), respectively, at the pN center-of-mass energy $\sqrt{s}$; $\rho(\mathbf{r})$ and $P(\mathbf{p}_t, E)$ are the density and nuclear spectral function normalized to unity; $\mathbf{p}_t$ and E are the internal momentum and removal energy of the struck target nucleon just before the collision; $\sigma_{pN}^{\rm in}$ and $\Gamma_{\rm tot}(\mathbf{r}, M_\phi)$ are the inelastic cross section [4] of free pN interaction and total ϕ width in its rest frame, taken at the point $\mathbf{r}$ inside the nucleus and at the pole of the resonance; Z and N are the numbers of protons and neutrons in the target nucleus ($A = N + Z$), M_A and R are its mass and radius [5] ; m_N is the bare nucleon mass; $\mathbf{p}_0$ and E_0 are the momentum and total energy of the initial proton; V_0 is the nuclear optical potential that this proton, having the kinetic energy T_0 of about a few GeV, feels in the interior of the nucleus ($V_0 \approx 40$ MeV).

The first term in Eq. (4) describes the contribution to the ϕ meson production on nuclei from the primary pN interactions (1) and (2), whereas the second one represents the contribution to this production from the elementary process (3).

Let us now specify the off-shell differential cross sections $d\sigma_{pN\to pN\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)/d\mathbf{p}_\phi$ and $d\sigma_{pn\to d\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)/d\mathbf{p}_\phi$ for ϕ production in the reactions (1), (2) and (3), entering into Eqs. (4), (7), (8). Following refs. [4, 32, 39–41], we assume that these cross sections are equivalent to the respective on-shell cross sections calculated for the off-shell kinematics of the elementary processes (1)–(3). In our approach the differential cross sections for ϕ production in the reactions (1), (2) have been described by the three-body phase space calculations normalized to the corresponding total cross sections $\sigma_{pN\to pN\phi}(\sqrt{s})$ [4, 30]:

$$\frac{d\sigma_{pN\to pN\phi}(\sqrt{s}, M_\phi, \mathbf{p}_\phi)}{d\mathbf{p}_\phi} = \frac{\pi}{4E_\phi}\frac{\sigma_{pN\to pN\phi}(\sqrt{s})}{I_3(s, m_p, m_N, M_\phi)}\frac{\lambda(s_{pN}, m_p^2, m_N^2)}{s_{pN}}, \tag{14}$$

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[3] The struck target nucleon is off-shell, see Eq. (13).

[4] We use $\sigma_{pN}^{\rm in} = 30$ mb for considered projectile proton energy of 2.83 GeV [33].

[5] It is determined from the relation $\rho_N(R) = 0.03\rho_0$ [1], where ρ_N is the nuclear density, and is equal to 4.0, 5.259, 6.112, 7.417, 8.737, 9.214 fm, respectively, for ^{12}C, ^{27}Al, ^{63}Cu, ^{108}Ag, ^{197}Au, ^{238}U target nuclei considered in the present work.

$$I_3(s,m_p,m_N,M_\phi)=(\frac{\pi}{2})^2\int\limits_{(m_p+m_N)^2}^{(\sqrt{s}-M_\phi)^2}\frac{\lambda(s_{pN},m_p^2,m_N^2)}{s_{pN}}\frac{\lambda(s,s_{pN},M_\phi^2)}{s}\,ds_{pN}, \quad (15)$$

$$\lambda(x,y,z)=\sqrt{\left[x-(\sqrt{y}+\sqrt{z})^2\right]\left[x-(\sqrt{y}-\sqrt{z})^2\right]}, \quad (16)$$

$$s_{pN}=s+M_\phi^2-2(E_0^{'}+E_t)E_\phi+2({\bf p}_0^{'}+{\bf p}_t){\bf p}_\phi. \quad (17)$$

Here, E_ϕ is the total energy of a ϕ meson ($E_\phi=\sqrt{p_\phi^2+M_\phi^2}$).

For the free total cross section $\sigma_{pp\to pp\phi}(\sqrt{s})$ we have used the following parametrization:

$$\sigma_{pp\to pp\phi}(\sqrt{s})=10\left(1-\frac{s_{th}}{s}\right)^{1.26}\left(\frac{s_{th}}{s}\right)^{1.66}\;[\mu{\rm b}], \quad (18)$$

where $\sqrt{s_{th}}=2m_p+M_\phi$ is the threshold energy for $pp\to pp\phi$ reaction. The comparison of the results of our calculations by (18) (dotted line) with the experimental data (full squares) close to the threshold for this reaction from the installation ANKE-at-COSY [27] (three lowest data points corresponding to excess energies of 18.5, 34.5 and 75.9 MeV), from the DISTO Collaboration [42] (fourth data point at excess energy of 83 MeV) as well as from the measurement [43] at higher energy (data point at excess energy of 1.644 GeV) is shown in Fig. 1. It is seen that our parametrization (18) fits quite well the existing set of data for the $pp\to pp\phi$ reaction in the threshold region.

For obtaining the total cross section of the $pn\to pn\phi$ reaction, where data are not available, we have employed the following relation:

$$\sigma_{pn\to pn\phi}(\sqrt{s})=f\left(\sqrt{s}-\sqrt{s_{th}}\right)\sigma_{pp\to pp\phi}(\sqrt{s}). \quad (19)$$

In the literature there are [28, 29, 44, 45] a different options to choose the cross section ratio $f=\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ in the near-threshold energy regime. Thus, for instance, the authors of ref. [28] using their measurements of ϕ production in quasi-free $pn\to d\phi$ reaction close to threshold and final-state-interaction theory [46] have found that very near threshold this ratio can be estimated as:

$$f=\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}\approx 2.3. \quad (20)$$

We will use this value in the present study. To see the sensitivity of A-dependences of the absolute and relative ϕ production cross sections in proton–nucleus collisions to the experimentally unknown cross section ratio f, we will also adopt in our calculations instead of the above value the following dependence [6] :

$$f(\epsilon)=\left\{\begin{array}{ll} 3 & \mbox{for } 0<\epsilon\le 0.004 \mbox{ GeV},\\ 6.607\epsilon^{0.1430} & \mbox{for } 0.004 \mbox{ GeV}<\epsilon\le 0.007 \mbox{ GeV},\\ 6.882\epsilon^{0.1512} & \mbox{for } 0.007 \mbox{ GeV}<\epsilon\le 0.03 \mbox{ GeV},\\ 5.902\epsilon^{0.1074} & \mbox{for } 0.03 \mbox{ GeV}<\epsilon\le 0.08 \mbox{ GeV},\\ 5.074\epsilon^{0.0475} & \mbox{for } 0.08 \mbox{ GeV}<\epsilon\le 0.25 \mbox{ GeV},\\ 4.611\epsilon^{-0.0214} & \mbox{for } \epsilon>0.25 \mbox{ GeV}, \end{array}\right. \quad (21)$$

[6] The excess energy ϵ in this dependence is measured in GeV.

which, as is seen from Fig. 2, fits fairly well (solid line) the results of recent calculations [29] (full squares) of this ratio within an effective meson–nucleon theory. It is interesting to note that the main contribution to the ϕ production from the one-step reaction channels (1), (2) at 2.83 GeV incident energy of our interest with the use in the calculations the ratio f in the form (21) and with taking into account in them the kinematical acceptance conditions of the ANKE experiment [21, 22] at COSY comes from excess energies $\epsilon \geq 30$ MeV, where in line with Fig. 2 this ratio > 4. It is thus expected that the absolute ϕ yield from primary production processes (1), (2) will be enhanced when the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ in the form of (21) is used (see, also, below).

Taking into consideration the two-body kinematics of the elementary process (3), we can readily get the following expression for the differential cross section for ϕ production in this process (see, also, [30, 32]):

$$\frac{d\sigma_{pn\to d\phi}(\sqrt{s},M_{\phi},\mathbf{p}_{\phi})}{d\mathbf{p}_{\phi}}=\frac{\pi}{I_2(s,m_d,M_{\phi})E_{\phi}}\frac{d\sigma_{pn\to d\phi}(\sqrt{s})}{d\mathbf{\Omega}_{\phi}^{'}}\times \tag{22}$$

$$\times\frac{1}{(\omega+E_t)}\delta\left[\omega+E_t-\sqrt{m_d^2+(\mathbf{Q}+\mathbf{p}_t)^2}\right],$$

where

$$I_2(s,m_d,M_{\phi})=\frac{\pi}{2}\frac{\lambda(s,m_d^2,M_{\phi}^2)}{s}, \tag{23}$$

$$\omega=E_0^{'}-E_{\phi},\quad \mathbf{Q}=\mathbf{p}_0^{'}-\mathbf{p}_{\phi}. \tag{24}$$

Here, $d\sigma_{pn\to d\phi}(\sqrt{s})/d\mathbf{\Omega}_{\phi}^{'}$ is the differential cross section for ϕ production in reaction (3) in the pn c.m.s. normalized to the corresponding total experimental cross section $\sigma_{pn\to d\phi}$; m_d is the mass of a deuteron. The authors of ref. [28] have fitted their own experimental data on the total cross section $\sigma_{pn\to d\phi}$ close to threshold by the following simple expression:

$$\sigma_{pn\to d\phi}(\sqrt{s})=48\sqrt{(\epsilon_d/\mathrm{MeV})}\ [\mathrm{nb}], \tag{25}$$

where $\epsilon_d=\sqrt{s}-(m_d+M_{\phi})$ is the respective c.m.s. excess energy. This expression has been used in our calculations. In them, the angular distribution $d\sigma_{pn\to d\phi}(\sqrt{s})/d\mathbf{\Omega}_{\phi}^{'}$ was also assumed to be isotropic [28].

For the ϕ production calculations in the case of ^{12}C and ^{27}Al, ^{63}Cu, ^{108}Ag, ^{197}Au, ^{238}U target nuclei reported here we have employed for the nuclear density $\rho(\mathbf{r})$, respectively, the harmonic oscillator and the Woods-Saxon distributions:

$$\rho(\mathbf{r})=\rho_N(\mathbf{r})/A=\frac{(b/\pi)^{3/2}}{A/4}\left\{1+\left[\frac{A-4}{6}\right]br^2\right\}\exp{(-br^2)}, \tag{26}$$

$$\rho(\mathbf{r})=\rho_0\left[1+\exp\left(\frac{r-R_{1/2}}{a}\right)\right]^{-1} \tag{27}$$

with $b=0.355$ fm^{-2} [4] and $R_{1/2}=3.347$ fm for ^{27}Al, $R_{1/2}=4.20$ fm for ^{63}Cu, $R_{1/2}=5.505$ fm for ^{108}Ag, $R_{1/2}=6.825$ fm for ^{197}Au, $R_{1/2}=7.302$ fm for ^{238}U, $a=0.55$ fm for all nuclei [4, 47]. The nuclear spectral function $P(\mathbf{p}_t,E)$ (which represents the probability to find a nucleon with momentum $\mathbf{p}_t$ and removal energy E in the nucleus) for ^{12}C target nucleus was taken from [30]. The single-particle part

of this function for medium ^{27}Al, ^{63}Cu and heavy ^{108}Ag, ^{197}Au, ^{238}U target nuclei was assumed to be the same as that for ^{208}Pb [33, 34, 48]. The latter was taken from [32]. The correlated part of the nuclear spectral function for these target nuclei was borrowed from [30].

Let us concentrate now on the total ϕ in-medium width appearing in (6) and used in the subsequent calculations of phi meson attenuation in pA interactions.

For this width, the calculations foresee four different scenarios: **i)** no in-medium effects and, correspondingly, the scenario with the free ϕ width (dotted line in Fig. 3); **ii)** the same in-medium effects on the masses of a daughter kaon, antikaon ρ meson and through this on the ϕ decay width in a nuclear environment as well as the same collisional broadening [7] of a ϕ meson in this environment as those adopted before in [4] (solid line [8] in Fig. 3); **iii)** the same in-medium effects on the phi decay width as those in the preceding case and the collisional broadening of a ϕ meson, characterized by an enlarged phi collisional width of 25.4 MeV [9] at normal nuclear matter density to get for the total ϕ width at this density the value of about 45 MeV predicted in ref. [19] (dashed line in Fig. 3) and **iv)** the same in-medium effects on the phi decay width as those in the previous cases and the collisional broadening of a ϕ meson, determined by an increased phi collisional width of 40.4 MeV at nuclear density ρ_0 to gain for the ϕ total width at this density the value of the order of 60 MeV, which is twice the total width at ρ_0, used in the second scenario (dot-dashed line in Fig. 3). The parametrizations of [4] are taken here to calculate the density dependences of the ϕ decay and collisional widths. It should be noted that the adoption of the phi in-medium widths depicted in Fig. 3 is justified not only for small [4, 19], but also for high ϕ momenta falling in the range, at least, up to 2 GeV/c due to a relatively weak dependence of the imaginary part, $Im\Pi_{\phi}$, of the ϕ self-energy [10] in nuclear matter on its momentum in this range found in [8]. We are interested in the ϕ momentum region mentioned above in view of our intention to account for in our calculations of the phi production in proton–nucleus reactions the acceptance window of the ANKE spectrometer belonging namely to this region.

Let us consider now the two-step ϕ production mechanism.

2.2 Two-step ϕ production mechanism

At the bombarding energy of our interest (2.83 GeV) the following two-step ϕ production process with a pion [11] in an intermediate state may contribute to the phi production in pA interactions:

$$p + N_1 \to \pi + X, \tag{28}$$

$$\pi + N_2 \to \phi + N, \tag{29}$$

[7] Which is characterized by the collisional width of 10 MeV at saturation density ρ_0 [4].

[8] It shows that in this scenario the resulting total (decay+collisional) width of the ϕ meson grows as a function of the density and reaches the value of around 30 MeV at the density ρ_0.

[9] It should be pointed out that this value is close to the magnitude of the ϕ collisional width of 24 MeV obtained in [7] at nuclear density ρ_0 and vanishing ϕ momentum.

[10] Let us remind that this part is tied to the phi total width in its rest frame by the relation: $\Gamma_{\rm tot} = -Im\Pi_{\phi}/M_{\phi}$.

[11] Which is assumed to be on-shell.

provided that the latter subprocess is allowed energetically [12] . Taking into account the phi final-state absorption and ignoring the influence [13] of the nuclear environment on the outgoing hadron masses in the ϕ production channel (29) as well as using the results given in [33, 38], we get the following expression for the phi production cross section for pA reactions at small laboratory angles of interest from this channel:

$$\frac{d\sigma_{pA\to\phi X}^{(\rm sec)}({\bf p}_0)}{d{\bf p}_\phi} = \frac{I_V^{(\rm sec)}[A]}{I_V^{\prime}[A]} \sum_{\pi=\pi^+,\pi^0,\pi^-} \int\limits_{4\pi} d{\bf \Omega}_\pi \int\limits_{p_\pi^{\rm abs}}^{p_\pi^{\rm lim}(\vartheta_\pi)} p_\pi^2 dp_\pi \frac{d\sigma_{pA\to\pi X}^{(\rm prim)}({\bf p}_0)}{d{\bf p}_\pi} \times \tag{30}$$
$$\times \left[\frac{Z}{A}\left<\frac{d\sigma_{\pi p\to\phi N}({\bf p}_\pi,{\bf p}_\phi)}{d{\bf p}_\phi}\right> + \frac{N}{A}\left<\frac{d\sigma_{\pi n\to\phi N}({\bf p}_\pi,{\bf p}_\phi)}{d{\bf p}_\phi}\right>\right],$$

where

$$I_V^{(\rm sec)}[A] = 2\pi A^2 \int\limits_0^R r_\perp dr_\perp \int\limits_{-\sqrt{R^2-r_\perp^2}}^{\sqrt{R^2-r_\perp^2}} dz\rho(\sqrt{r_\perp^2+z^2}) \int\limits_0^{\sqrt{R^2-r_\perp^2}-z} dl\rho(\sqrt{r_\perp^2+(z+l)^2}) \times \tag{31}$$
$$\times \exp\left[-\sigma_{pN}^{\rm in}A \int\limits_{-\sqrt{R^2-r_\perp^2}}^{z} \rho(\sqrt{r_\perp^2+x^2})dx - \sigma_{\pi N}^{\rm tot}A \int\limits_z^{z+l} \rho(\sqrt{r_\perp^2+x^2})dx\right] \times$$
$$\times \exp\left[-\int\limits_{z+l}^{\sqrt{R^2-r_\perp^2}} \frac{dx}{\lambda_\phi(\sqrt{r_\perp^2+x^2},M_\phi)}\right],$$

$$I_V^{\prime}[A] = 2\pi A \int\limits_0^R r_\perp dr_\perp \int\limits_{-\sqrt{R^2-r_\perp^2}}^{\sqrt{R^2-r_\perp^2}} dz\rho(\sqrt{r_\perp^2+z^2}) \times \tag{32}$$
$$\times \exp\left[-\sigma_{pN}^{\rm in}A \int\limits_{-\sqrt{R^2-r_\perp^2}}^{z} \rho(\sqrt{r_\perp^2+x^2})dx - \sigma_{\pi N}^{\rm tot}A \int\limits_z^{\sqrt{R^2-r_\perp^2}} \rho(\sqrt{r_\perp^2+x^2})dx\right],$$

$$\left<\frac{d\sigma_{\pi N\to\phi N}({\bf p}_\pi,{\bf p}_\phi)}{d{\bf p}_\phi}\right> = \int\int P({\bf p}_t,E)d{\bf p}_t dE \left[\frac{d\sigma_{\pi N\to\phi N}(\sqrt{s_1},{\bf p}_\phi)}{d{\bf p}_\phi}\right]; \tag{33}$$

$$s_1 = (E_\pi+E_t)^2 - (p_\pi{\bf \Omega_0}+{\bf p}_t)^2, \tag{34}$$

$$p_\pi^{\rm lim}(\vartheta_\pi) = \frac{\beta_A p_0\cos\vartheta_\pi + (E_0+M_A)\sqrt{\beta_A^2-4m_\pi^2(s_A+p_0^2\sin^2\vartheta_\pi)}}{2(s_A+p_0^2\sin^2\vartheta_\pi)}, \tag{35}$$

$$\beta_A = s_A + m_\pi^2 - M_{A+1}^2,\;\; s_A = (E_0+M_A)^2 - p_0^2, \tag{36}$$

$$\cos\vartheta_\pi = {\bf \Omega}_0{\bf \Omega}_\pi, \quad {\bf \Omega}_0 = {\bf p}_0/p_0, \quad {\bf \Omega}_\pi = {\bf p}_\pi/p_\pi. \tag{37}$$

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[12] We remind that the free threshold energy for this subprocess amounts to 1.43 GeV.

[13] In line with the assumption about the absence of such influence on the final hadron masses in primary proton-induced reaction channels (1)–(3).

Here, $d\sigma^{(\mathrm{prim})}_{pA\to\pi X}(\mathbf{p}_0)/d\mathbf{p}_\pi$ are the inclusive differential cross sections for pion production on nuclei at small laboratory angles and for high momenta from the primary proton-induced reaction channel (28); $d\sigma_{\pi N\to\phi N}(\sqrt{s_1},\mathbf{p}_\phi)/d\mathbf{p}_\phi$ is the free inclusive differential cross section for ϕ production via the subprocess (29) calculated for the off-shell kinematics of this subprocess at the πN center-of-mass energy $\sqrt{s_1}$; $\sigma^{\mathrm{tot}}_{\pi N}$ is the total cross section of the free πN interaction [14] ; $\mathbf{p}_\pi$ and E_π are the momentum and total energy of a pion; p^{abs}_π is the absolute threshold momentum for phi production on the residual nucleus by an intermediate pion; $p^{\mathrm{lim}}_\pi(\vartheta_\pi)$ is the kinematical limit for pion production at the lab angle ϑ_π from proton-nucleus collisions. The quantity λ_ϕ is defined above by Eq. (6).

The expression for the differential cross section for ϕ production in the elementary process (29) has the form similar to that (22) for proton-induced reaction (3):

$$\frac{d\sigma_{\pi N\to\phi N}(\sqrt{s_1},\mathbf{p}_\phi)}{d\mathbf{p}_\phi}=\frac{\pi}{I_2(s_1,m_N,M_\phi)E_\phi}\frac{d\sigma_{\pi N\to\phi N}(\sqrt{s_1})}{d\mathbf{\Omega}^*_\phi}\times \tag{38}$$

$$\times\frac{1}{(\omega_1+E_t)}\delta\left[\omega_1+E_t-\sqrt{m_N^2+(\mathbf{Q}_1+\mathbf{p}_t)^2}\right],$$

where

$$\omega_1=E_\pi-E_\phi,\quad \mathbf{Q}_1=\mathbf{p}_\pi-\mathbf{p}_\phi \tag{39}$$

and the quantity I_2 is defined above by Eq. (23). In Eq. (38), $d\sigma_{\pi N\to\phi N}(\sqrt{s_1})/d\mathbf{\Omega}^*_\phi$ is the differential cross section for ϕ production in reaction (29) in the πN c.m.s., which is assumed to be isotropic [1, 49] in our calculations of phi creation in pA collisions from this reaction:

$$\frac{d\sigma_{\pi N\to\phi N}(\sqrt{s_1})}{d\mathbf{\Omega}^*_\phi}=\frac{\sigma_{\pi N\to\phi N}(\sqrt{s_1})}{4\pi}. \tag{40}$$

Here, $\sigma_{\pi N\to\phi N}(\sqrt{s_1})$ is the total cross section of the elementary process $\pi N\to\phi N$. The elementary ϕ production reactions $\pi^+n\to\phi p$, $\pi^0p\to\phi p$, $\pi^0n\to\phi n$ and $\pi^-p\to\phi n$ have been included in our calculations of the ϕ production on nuclei. The isospin considerations show that the following relations among the total cross sections of these reactions exist [50]:

$$\sigma_{\pi^+n\to\phi p}=\sigma_{\pi^-p\to\phi n}, \tag{41}$$

$$\sigma_{\pi^0p\to\phi p}=\sigma_{\pi^0n\to\phi n}=\frac{1}{2}\sigma_{\pi^-p\to\phi n}. \tag{42}$$

For the free total cross section $\sigma_{\pi^-p\to\phi n}$ we have used the following parametrization suggested in [51]:

$$\sigma_{\pi^-p\to\phi n}(\sqrt{s_1})=\begin{cases}0.47\left(\sqrt{s_1}-\sqrt{s_0}\right)\ [\mathrm{mb}] & \text{for } \sqrt{s_0}<\sqrt{s_1}<2.05\ \mathrm{GeV},\\[2ex] 23.7/s_1^{4.4}\ [\mathrm{mb}] & \text{for } \sqrt{s_1}\geq 2.05\ \mathrm{GeV},\end{cases} \tag{43}$$

where $\sqrt{s_0}=m_n+M_\phi$ is the threshold energy.

[14] We use in the following calculations $\sigma^{\mathrm{tot}}_{\pi N}=35$ mb for all pion momenta [33].

It should be noted that for the cross section $\sigma_{\pi^- p\to\phi n}$ we have also adopted another parametrization:

$$\sigma_{\pi^- p\to\phi n}(\sqrt{s_1}) = \begin{cases} 0.101\left(\sqrt{s_1}-\sqrt{s_0}\right)^{0.466}\ [\mathrm{mb}] & \text{for } \sqrt{s_0} < \sqrt{s_1} < 2.08\ \mathrm{GeV}, \\ 23.7/s_1^{4.4}\ [\mathrm{mb}] & \text{for } \sqrt{s_1} \geq 2.08\ \mathrm{GeV}, \end{cases} \quad (44)$$

which combines the relevant parametrization from [50] in the "low" energy region with that given by Eq. (43) in the "high" energy region. The parametrization (44) is close to the results from the boson-exchange model [52] near the threshold, where the data are not available, and is considerably larger here than the one given above by Eq. (43). However, its use instead of (43), as showed our calculations, leads to increase of the relative cross sections for ϕ production in pA collisions of main interest only by about two percents at beam energy of 2.83 GeV. Therefore, this gives confidence to us that the expression (43) is reliable enough to describe the ϕ production in these collisions through the $\pi N \to \phi N$ reactions. We will employ this expression throughout our calculations.

Another a very important ingredients for the calculation of the phi production cross section in proton–nucleus reactions from pion-induced reaction channel (29)–the high momentum parts of the differential cross sections for pion production on nuclei at small lab angles from the primary process (28)–for ^{63}Cu target nucleus were taken from [33]. For ϕ production calculations in the case of ^{12}C and ^{27}Al, ^{108}Ag, ^{197}Au, ^{238}U target nuclei presented below we have supposed [34] that the ratio of the differential cross section for pion creation on ^{12}C and on these nuclei from the primary process (28) to the effective number [15] of nucleons participating in it is the same as that for ^{9}Be and ^{63}Cu adjusted for the kinematics relating, respectively, to ^{12}C and ^{27}Al, ^{108}Ag, ^{197}Au, ^{238}U.

Now, let us proceed to the discussion of the results of our calculations for phi production in pA interactions in the framework of the model outlined above.

3 Results and discussion

At first, we consider the A-dependences of the absolute ϕ production cross sections from the one-step and two-step phi creation mechanisms in pA collisions calculated on the basis of Eqs. (4), (30) for proton kinetic energy of 2.83 GeV in two scenarios for the total ϕ in-medium width as well as with imposing the ANKE spectrometer kinematical cuts on the laboratory phi momenta and production angles. These dependences are depicted in Figs. 4 and 5. Looking at these figures, one can see that the one-step ϕ production process $pn \to d\phi$, with the kinematic cuts imposed, plays a minor role for all considered target nuclei, whereas the role of secondary pion-induced reaction channel $\pi N \to \phi N$ is not negligible compared to that of primary $pN \to pN\phi$ processes in the chosen kinematics for nuclei larger than ^{27}Al especially in the case when the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ was taken to be equal to 2.3 [16] . This means that the channel $\pi N \to \phi N$ has to be taken into consideration

[15] Which is given by Eq. (32).

[16] For small nuclei ^{12}C and ^{27}Al the primary processes (1), (2), as can be seen from Figs. 4 and 5, clearly dominate the ϕ production for both options (20), (21) for the ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$. It

on close examination of the A-dependence of the relative ϕ meson production cross section in proton–nucleus reactions at energies just above threshold with the aim of extracting of the information on the ϕ width in nuclear medium. Comparing the curves, corresponding to the calculations of the ϕ yield from the primary $pN \to pN\phi$ processes (1), (2) for the two employed options for the ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$, one can also see that the use for this ratio the excess-energy-dependent form (21) leads to increase of the phi yield from these processes by about a factor of 2 compared to that obtained in the case when this ratio amounts to 2.3 for both considered scenarios for the ϕ width. This observation can be useful to help constrain the above ratio from the study of the ϕ meson production in near-threshold proton–nucleus collisions. Comparing Figs. 4 and 5, we see yet that the results of calculations presented in Fig. 5 are reduced (by a factor of about two) for heavy nuclei compared to those shown in Fig. 4 due to the increased phi width in the medium and, hence, the ϕ absorption here, in the case of Fig. 5.

We, therefore, come to the conclusion that the in-medium properties of the phi should be in principle observable through the target mass dependence of the absolute ϕ production cross section in pA reactions at above threshold beam energies.

However, the authors of ref. [3] have suggested to use as a measure for the ϕ meson width in nuclei the following relative observable–the double ratio: $R(^{A}X)/R(^{12}\mathrm{C}) = (\sigma_{pA\to\phi X}/A)/(\sigma_{p^{12}\mathrm{C}\to\phi X}/12)$, i.e. the ratio of the nuclear total phi production cross section from pA reactions divided by A to the same quantity on ^{12}C. But instead of this ratio, we consider the following analogous ratio $R(^{A}X)/R(^{12}\mathrm{C}) = (\tilde{\sigma}_{pA\to\phi X}/A)/(\tilde{\sigma}_{p^{12}\mathrm{C}\to\phi X}/12)$, where $\tilde{\sigma}_{pA\to\phi X}$ is the nuclear cross section for ϕ production from proton–nucleus collisions in the ANKE acceptance window: 0.6 GeV/c $\leq p_{\phi} \leq$ 1.8 GeV/c and $0^{\circ} \leq \theta_{\phi} \leq 8^{\circ}$. It is clear that our predictions for the latter ratio could be directly compared with the future data from the ANKE experiment [21, 22] to extract the definite information on the ϕ width in the nuclear matter.

Figure 6 shows the ratio $R(^{A}X)/R(^{12}\mathrm{C})=(\tilde{\sigma}_{pA\to\phi X}/A)/(\tilde{\sigma}_{p^{12}\mathrm{C}\to\phi X}/12)$ as a function of the nuclear mass number A calculated on the basis of Eqs. (4), (30) for the one-step and one- plus two-step ϕ creation mechanisms (corresponding lines with a shorthand symbols "prim" and "prim+sec" by them) for the projectile energy of 2.83 GeV as well as for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi} = 2.3$ and within the first two scenarios for the ϕ in-medium width: **i)** free phi width (dotted lines), **ii)** in-medium phi width shown by solid curve in Fig. 3 (solid lines). The same as in Fig. 6, but calculated for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ in the excess-energy-dependent form (21) is given in Fig. 7. It can be seen that there are clear differences between the results obtained by using, on the one hand, different ϕ in-medium widths under consideration and the same assumptions concerning the phi production mechanism (between corresponding dotted and solid lines), and, on the other hand, different suppositions about the ϕ creation mechanism and the same phi widths in the medium (between dotted lines, and between solid lines) for both considered choices for the quantity $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$. We may see, for example, that for heavy nuclei, where the ϕ absorption is enhanced, the calculated ratio $R(^{A}X)/R(^{12}\mathrm{C})$ can be of the order of 0.29 and 0.43 for the direct ϕ production mechanism as well as 0.35 and 0.55 for the direct plus two-step phi creation mechanisms in the cases when

should be noted that this fact is in line with the conclusion deduced in [53] about the dominant role of the direct ϕ production mechanism in the above threshold phi creation in p^{12}C interactions.

the absorption of phi mesons in nuclear matter was determined, respectively, by their in-medium width shown by solid curve in Fig. 3 and by their free width. Therefore, we can conclude that the observation of the A-dependence, like that just considered, can serve as an important tool to determine the ϕ width in nuclei and in the analysis of the observed dependence it is needed to account for the secondary pion-induced phi production processes.

In Fig. 8 we show together the results of our calculations, given before separately in Figs. 6, 7, for the A-dependence of present interest for the primary (1)–(3) plus secondary (29) ϕ production processes obtained for bombarding energy of 2.83 GeV by employing in them both the free phi mesons width (dotted lines) and their in-medium width shown by solid curve in Fig. 3 (solid lines) as well as the two options [17] for the ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ to see more clearly the sensitivity of the calculated A-dependence to this ratio. One can see that the differences between the calculations for the same ϕ widths with adopting for the quantity $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ two options (20), (21) are insignificant (within a several percents), which means that this experimentally unknown quantity has [18] a weak effect on the relative observable under consideration. Therefore, this observable can indeed be useful to help determine the phi width in the medium.

Finally, in Fig. 9 we show the predictions of our model for the double ratio $R(^AX)/R(^{12}\mathrm{C})$ of interest obtained for initial energy of 2.83 GeV by considering primary proton–nucleon (1)–(3) and secondary pion–nucleon (29) ϕ production processes as well as by using for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ the excess-energy-dependent form (21) and for the ϕ in-medium width those shown by dashed and dot-dashed curves in Fig. 3 (respectively, dashed and dot-dashed lines in Fig. 9) in comparison to the previously performed calculations with employing for this width the free one (dotted line in Fig. 9) and that depicted by solid curve in Fig. 3 (solid line in Fig. 9). We observe in this figure the visible differences between all calculations corresponding to different scenarios for the ϕ width in nuclei, which means that the future data from the ANKE-at-COSY experiment [21, 22] should help, as one may hope, to distinguish between these scenarios.

Thus, consistent with previous findings of [3], our present results demonstrate that the measurements of the A-dependence of the relative cross section for phi production in pA reactions in the considered kinematics and at above threshold beam energies will allow indeed to shed light on the ϕ in-medium properties. They show also that to extract the definite information on the ϕ width in nuclear matter from the analysis of the measured such dependence it is needed to take into account in this analysis the secondary pion-induced phi production processes.

4 Summary

In this paper we have calculated the A-dependences of the absolute and relative cross sections for ϕ production from pA reactions at 2.83 GeV beam energy by considering incoherent primary proton–nucleon and secondary pion–nucleon phi

[17] Indicated by the respective symbols by the lines.

[18] Contrary to our previous findings of Figs. 4 and 5 where its influence on the absolute ϕ production cross sections was found to be essential.

production processes in the framework of a nuclear spectral function approach [4, 30–34], which takes properly into account the struck target nucleon momentum and removal energy distribution, novel elementary cross sections for proton–nucleon reaction channel close to threshold as well as different scenarios for the total ϕ width in the medium, for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ and the ANKE spectrometer kinematical cuts on the laboratory phi momenta and production angles. It was found that the secondary pion-induced reaction channel $\pi N \to \phi N$ contributes distinctly to the ϕ production in heavy nuclei in the chosen kinematics and, hence, it has to be taken into consideration on close examination of the A-dependences of the ϕ meson production cross sections in pA interactions with the aim to get information on the phi width in the nuclear matter. It was also shown that the experimentally unknown cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ has, contrary to our findings for the absolute phi production cross sections, a weak effect on the A-dependence of the relative ϕ meson production cross section from pA collisions in the considered kinematics and at incident energy of interest, whereas it was found to be appreciably sensitive to the absorption of the ϕ in the surrounding nuclear matter in its way out of the nucleus, which is governed in turn by its in-medium width. This gives a nice opportunity to obtain the definite information on the ϕ width in the nuclear medium at finite baryon densities from the direct comparison the results of our present calculations for this relative observable with the future data from the recently performed ANKE-at-COSY experiment [21, 22].

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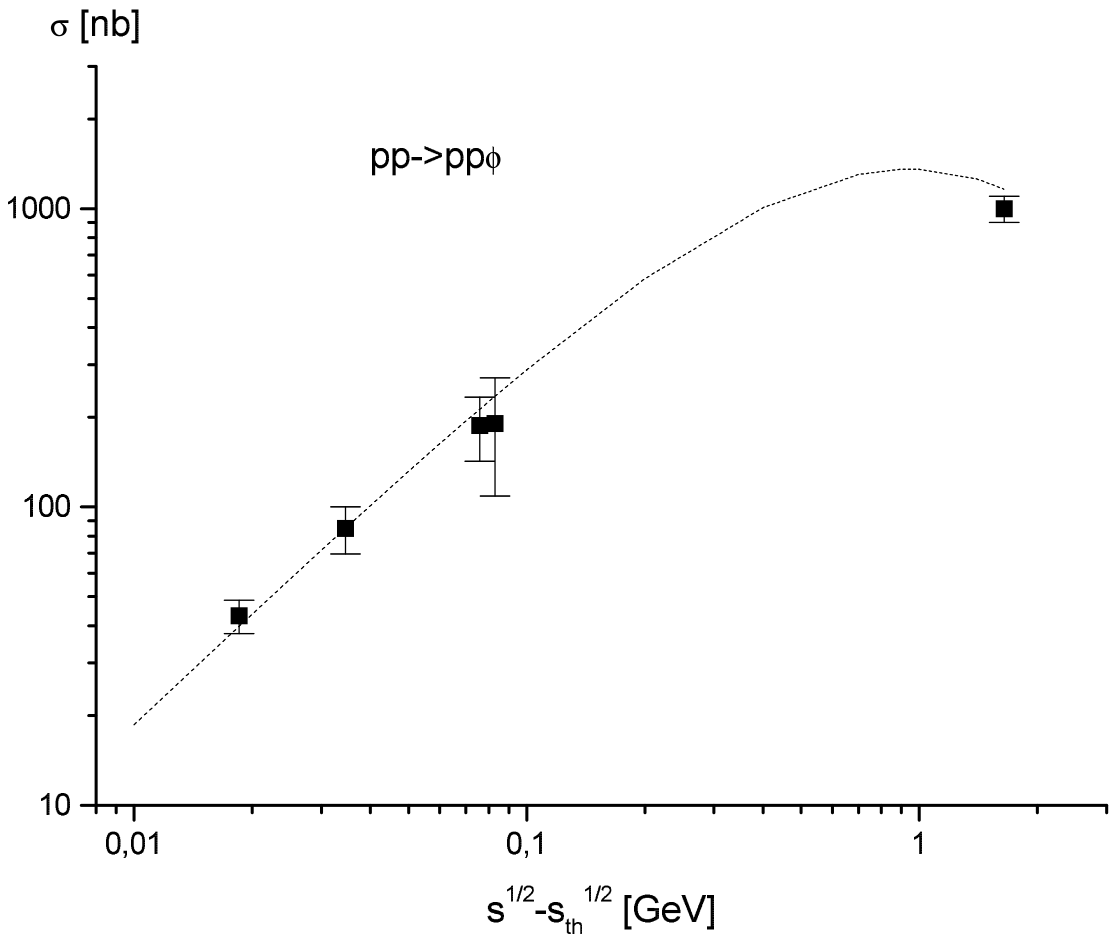

Figure 1: Total cross section for ϕ production in the reaction $pp \to pp\phi$ as a function of excess energy $\sqrt{s} - \sqrt{s_{th}}$. For notation see the text.

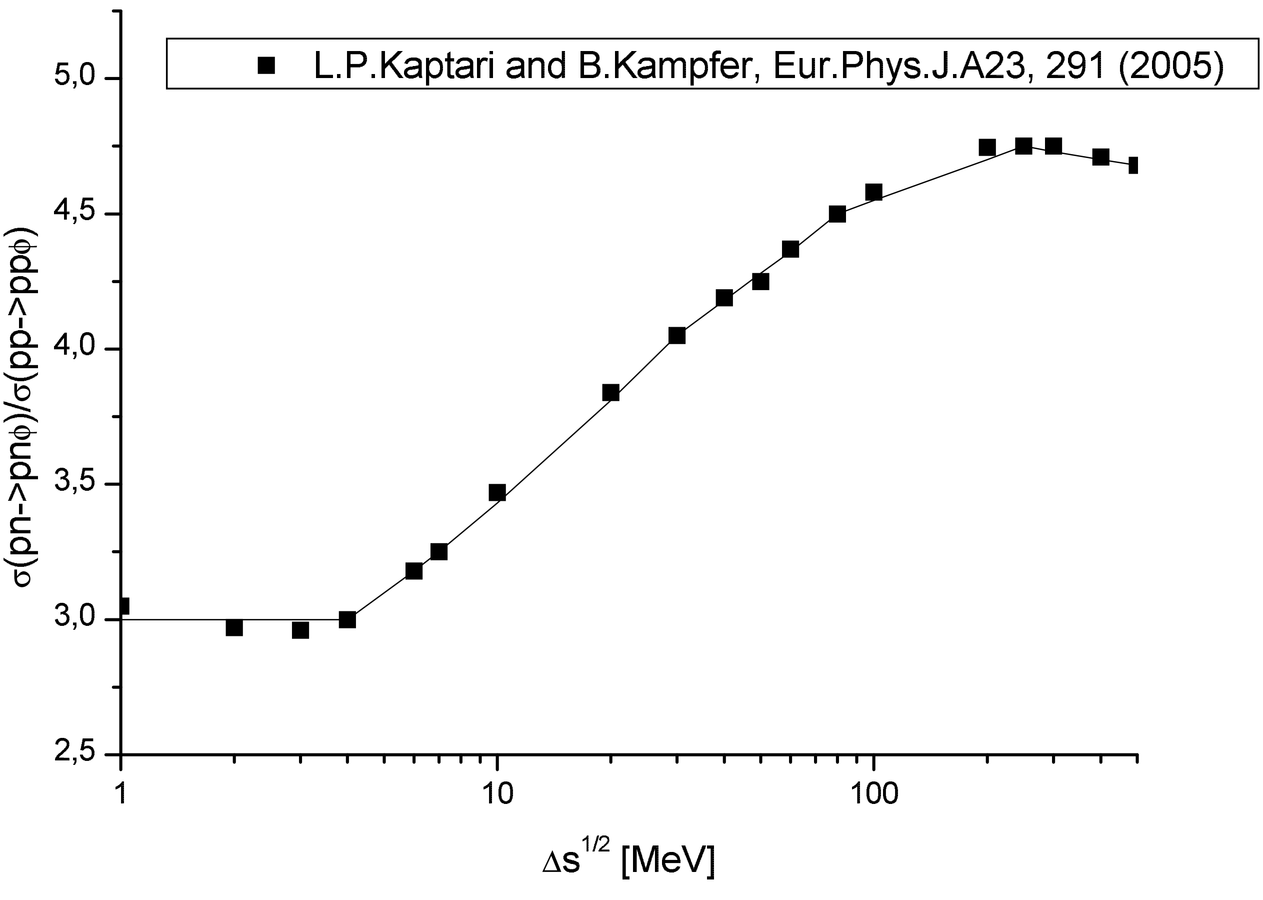

Figure 2: Ratio of the total cross sections of ϕ meson production in pp and pn channels. For notation see the text.

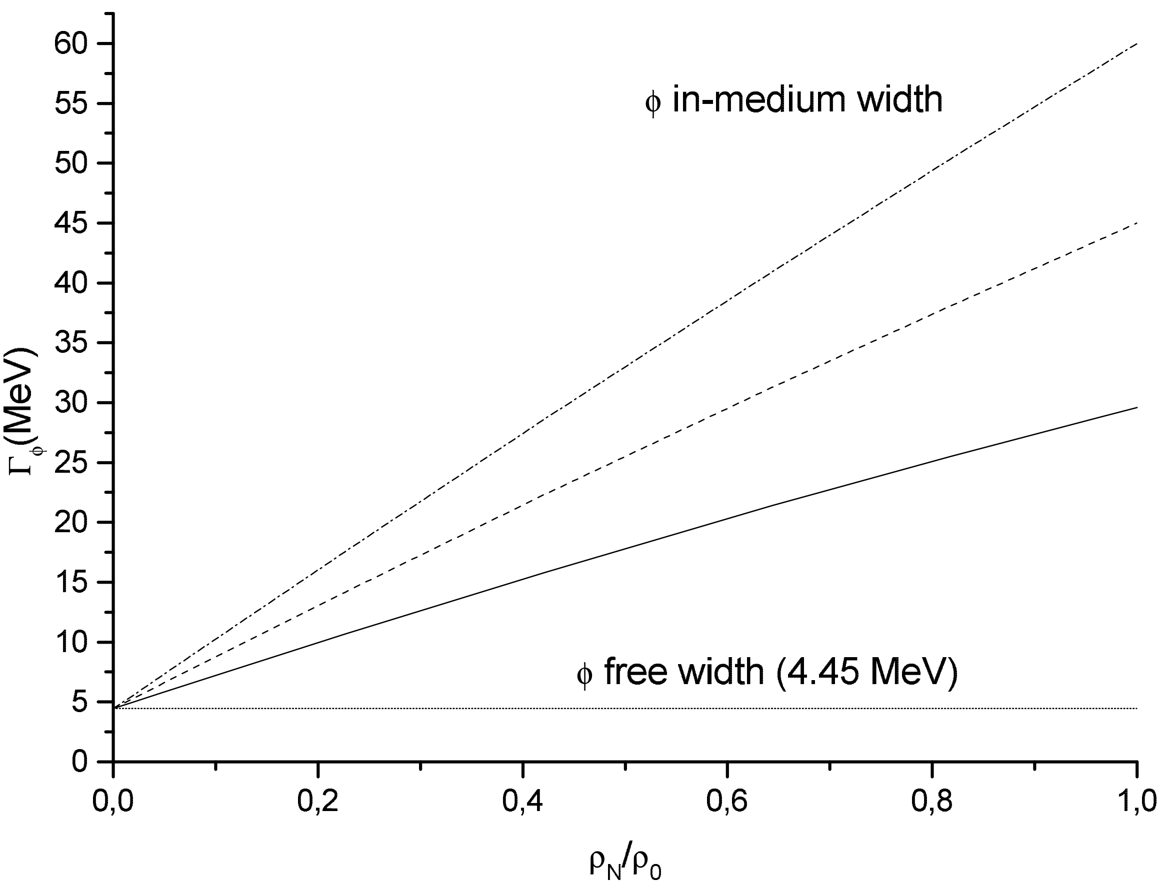

Figure 3: Phi meson total width as a function of density. For notation see the text.

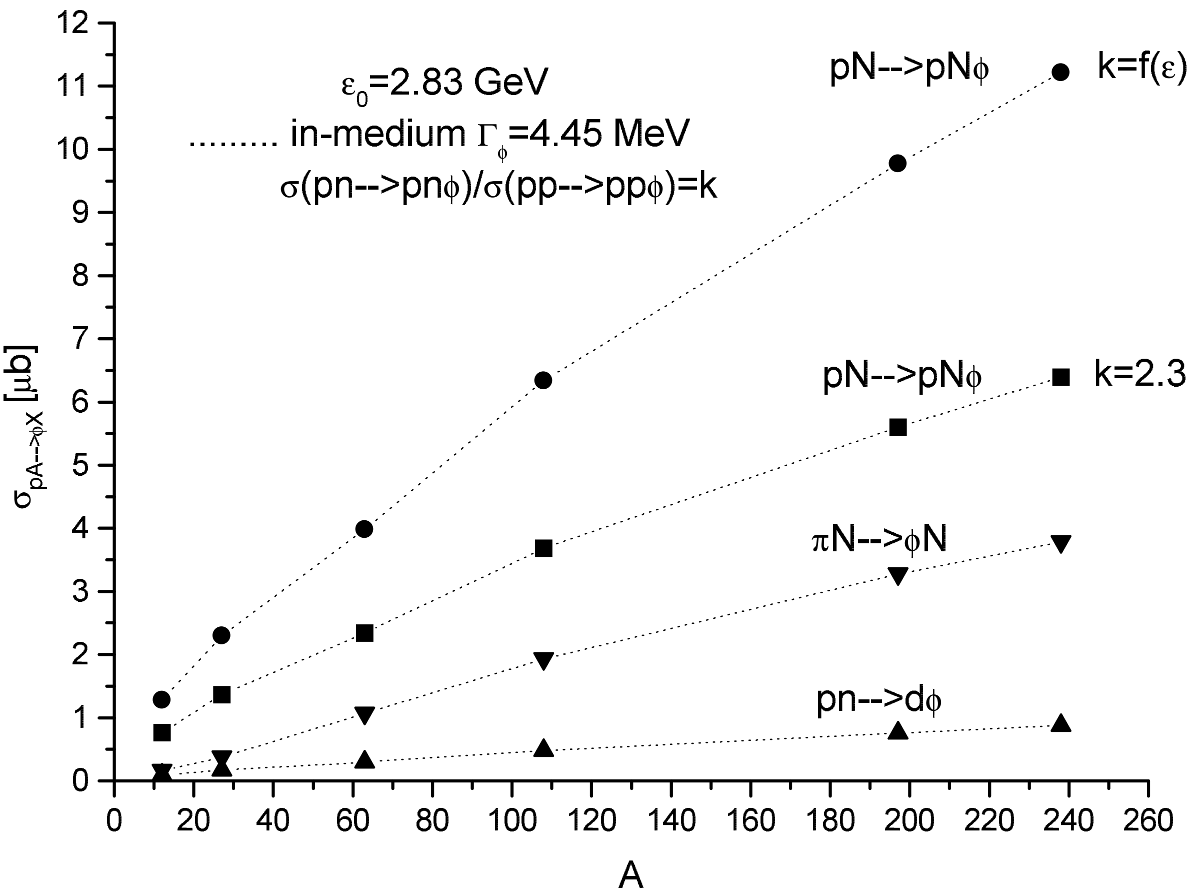

Figure 4: A-dependences of the total cross sections of ϕ production by 2.83 GeV protons from primary $pN \to pN\phi$ channels (1), (2) for two options (20), (21) for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$, from $pn \to d\phi$ process (3) as well as from secondary $\pi N \to \phi N$ channel (29) in the phi momentum range 0.6 GeV/c $\leq p_\phi \leq$ 1.8 GeV/c and in the phi polar angle domain $0^\circ \leq \theta_\phi \leq 8^\circ$ in the lab system–regions which are considered in the analysis of the ANKE-at-COSY experiment [21, 22]. The absorption of phi mesons in nuclear matter was determined by their free width (dotted curve in Fig. 3). The lines are included to guide the eyes.

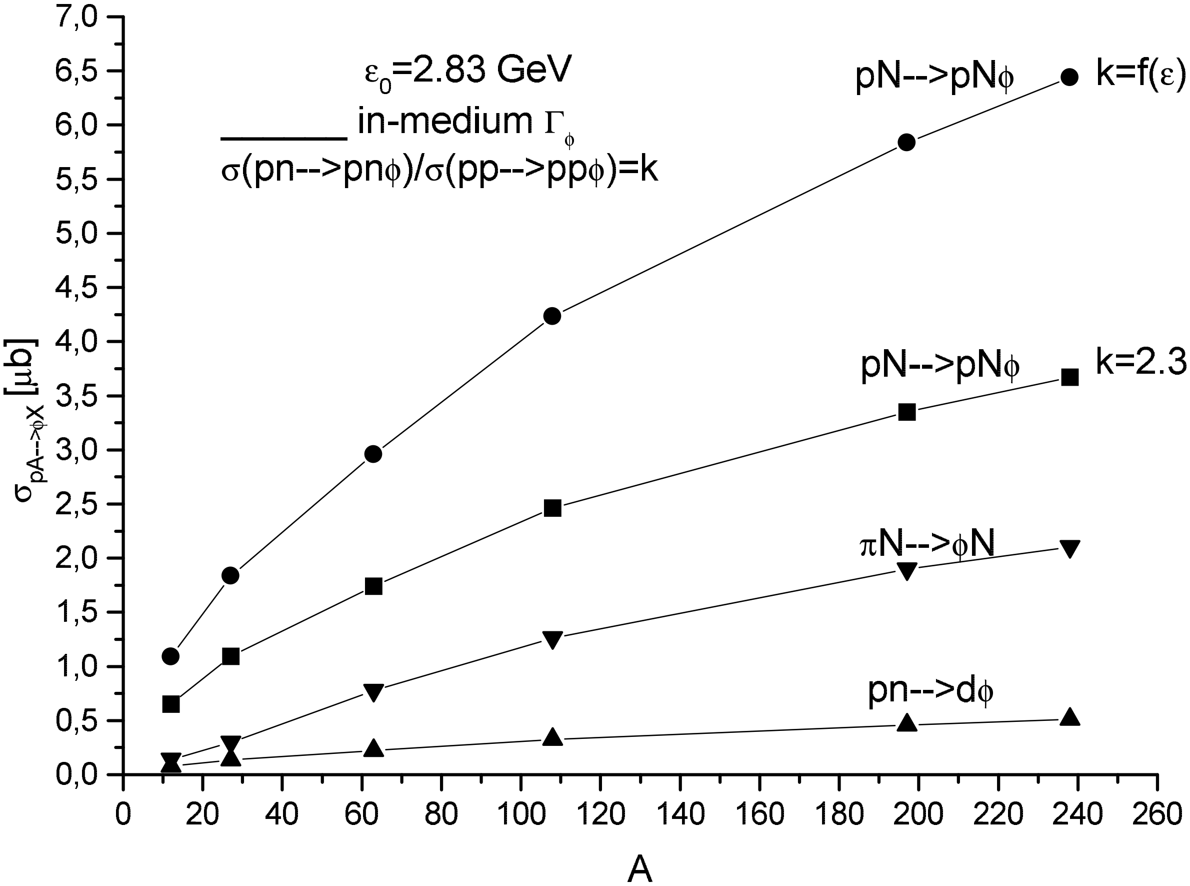

Figure 5: The same as in Fig. 4, but it is supposed that the absorption of phi mesons in nuclear matter was governed by their in-medium width shown by solid curve in Fig. 3.

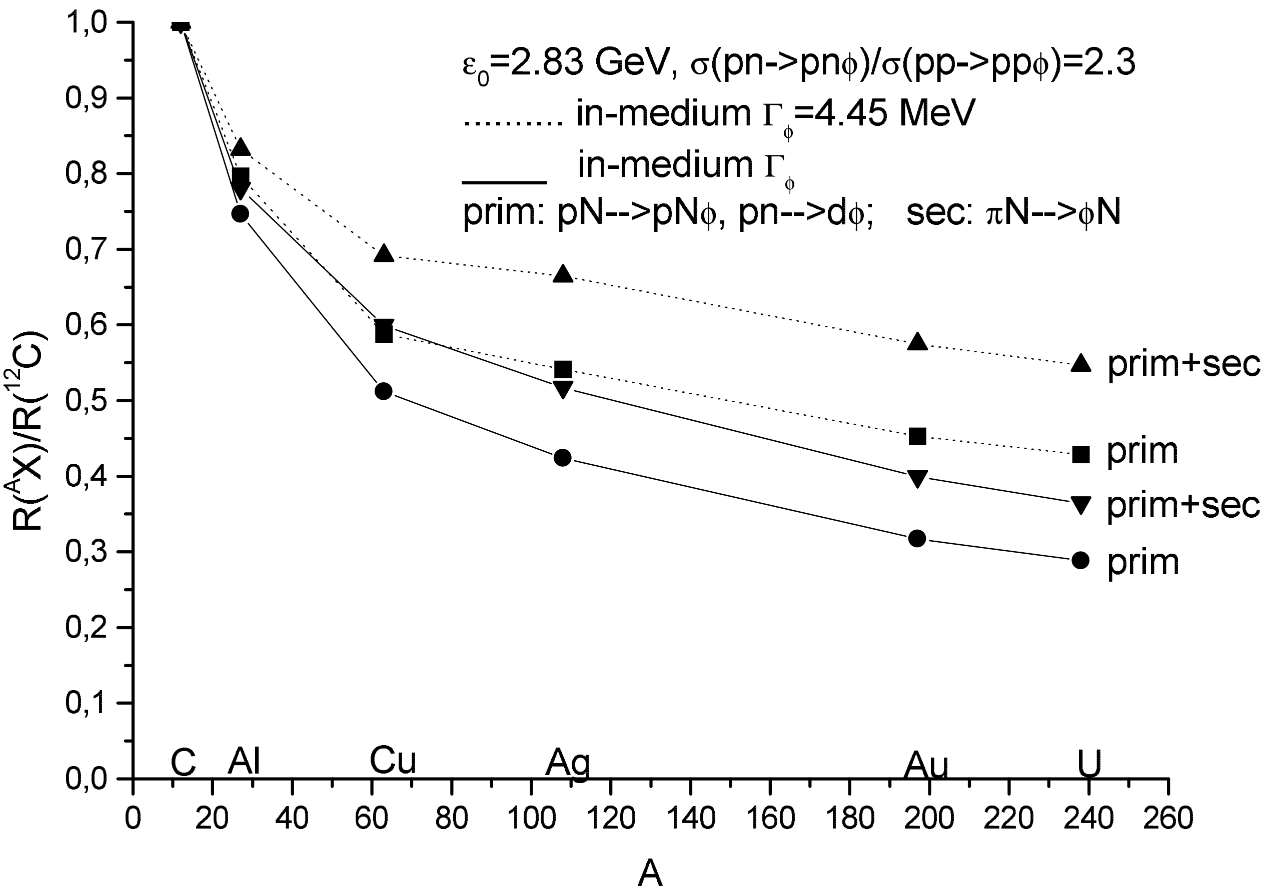

Figure 6: Ratio $R(^AX)/R(^{12}\mathrm{C})$= $(\tilde{\sigma}_{pA\to\phi X}/A)/(\tilde{\sigma}_{p^{12}\mathrm{C}\to\phi X}/12)$ as a function of the nuclear mass number for initial energy of 2.83 GeV and for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}=2.3$ calculated within the different scenarios for the ϕ meson production mechanism and for its in-medium width. For notation see the text.

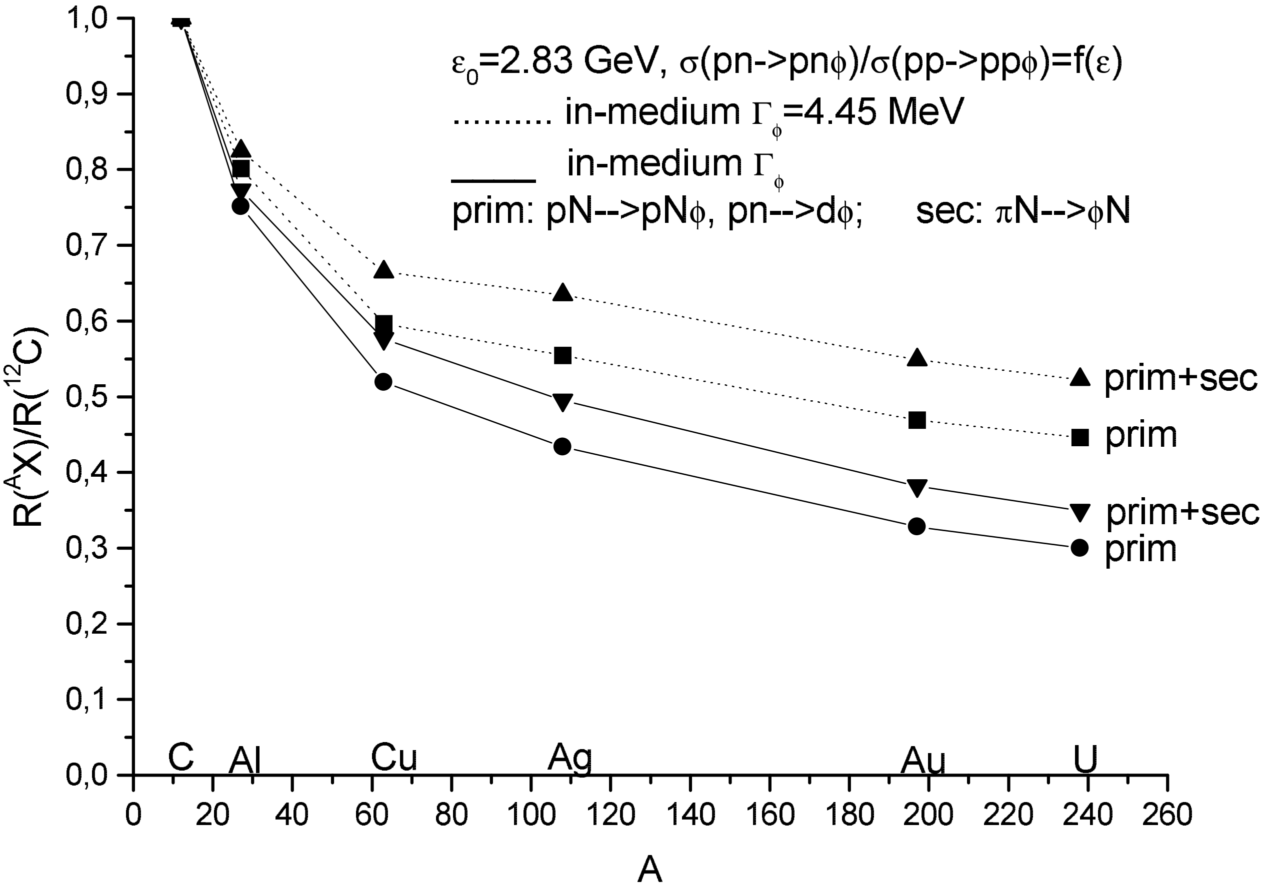

Figure 7: The same as in Fig. 6, but calculated for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ in the excess-energy-dependent form (21).

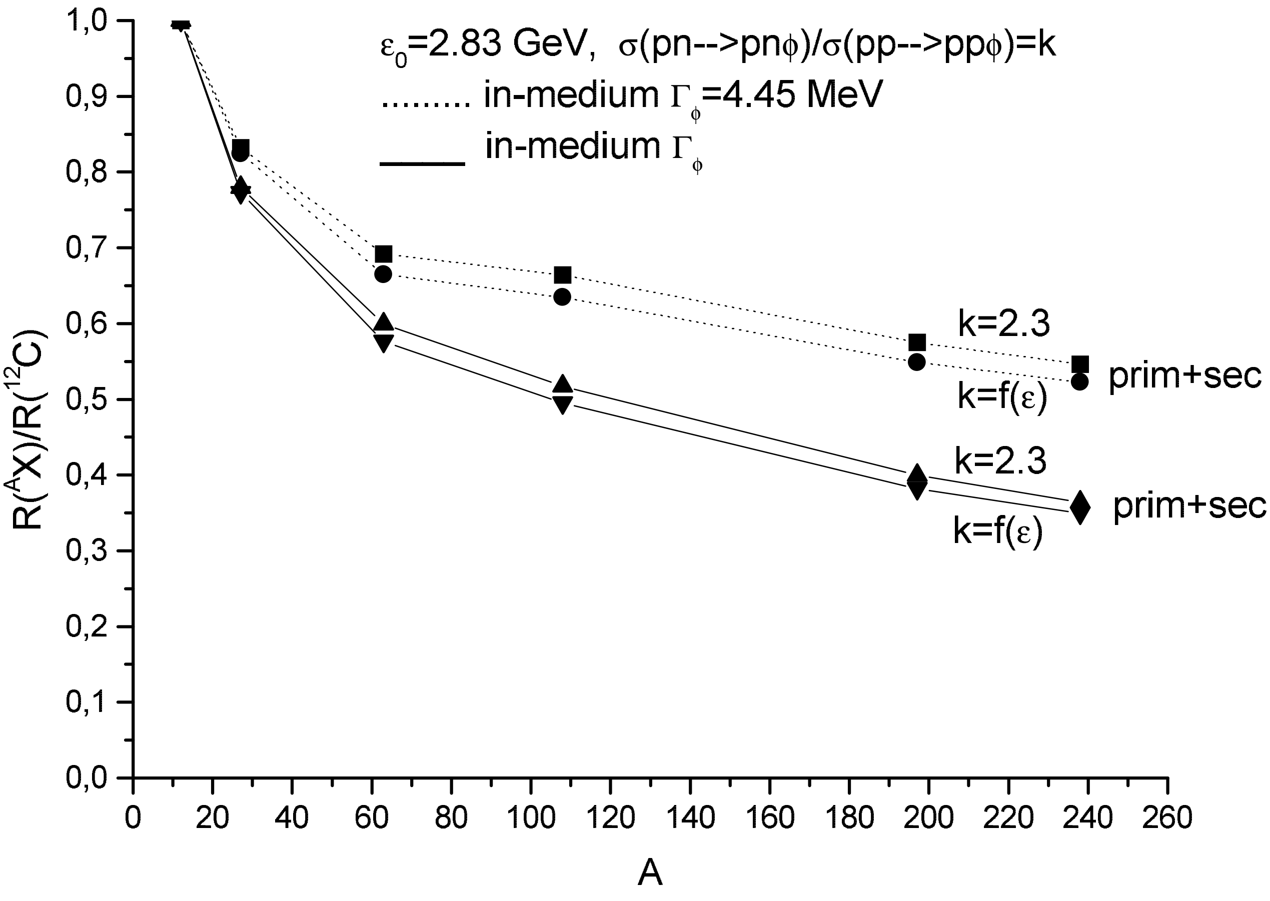

Figure 8: Ratio $R(^{A}X)/R(^{12}\mathrm{C})$= $(\tilde{\sigma}_{pA\to\phi X}/A)/(\tilde{\sigma}_{p^{12}\mathrm{C}\to\phi X}/12)$ as a function of the nuclear mass number for the one- plus two-step ϕ production mechanisms calculated for incident energy of 2.83 GeV within the different scenarios for the phi in-medium width and for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$. For notation see the text.

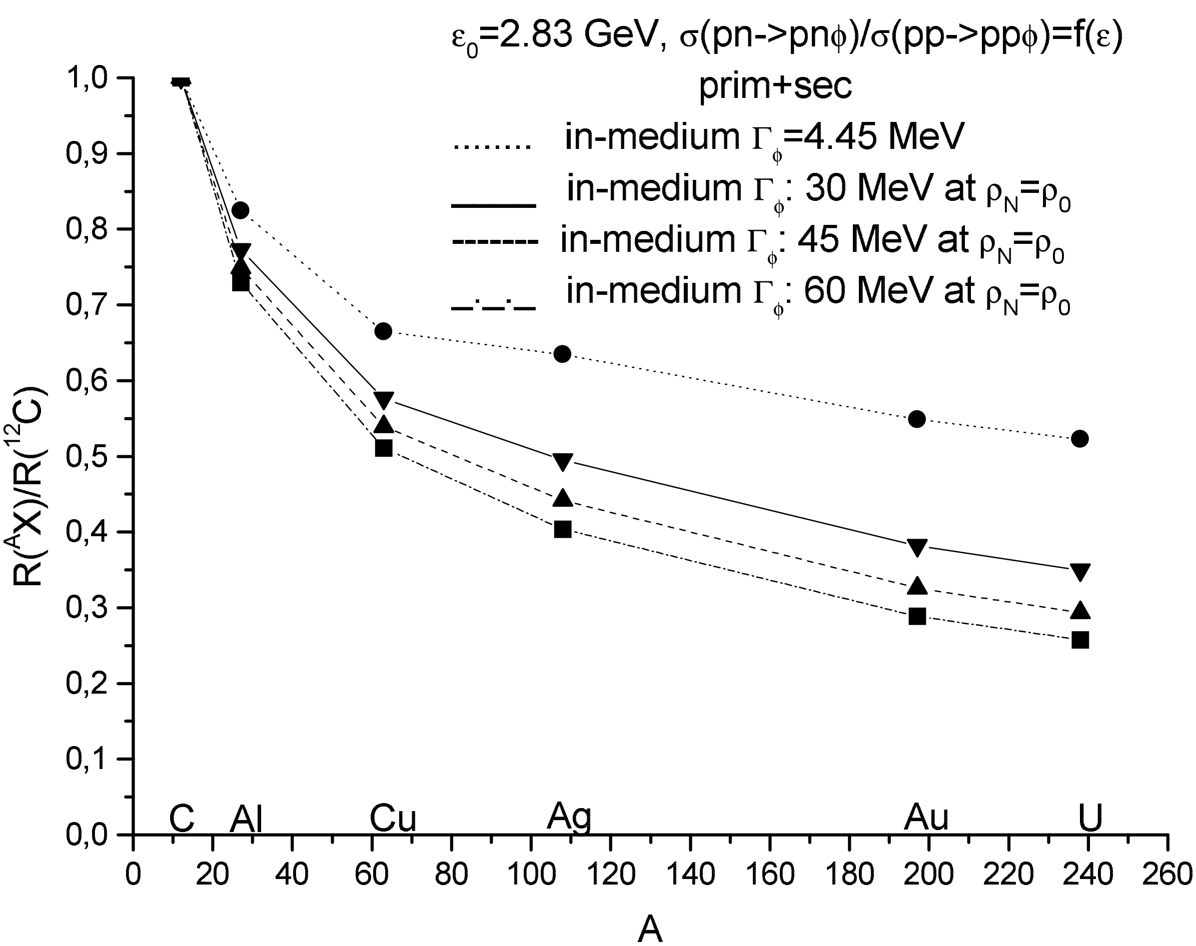

Figure 9: Ratio $R(^{A}X)/R(^{12}\mathrm{C})$= $(\tilde{\sigma}_{pA\to\phi X}/A)/(\tilde{\sigma}_{p^{12}\mathrm{C}\to\phi X}/12)$ as a function of the nuclear mass number for the one- plus two-step ϕ production mechanisms calculated for incident energy of 2.83 GeV and for the cross section ratio $\sigma_{pn\to pn\phi}/\sigma_{pp\to pp\phi}$ in the excess-energy-dependent form (21) within the different scenarios for the phi in-medium width. For notation see the text.